

**DETERMINING REFERENCE SPEED FROM PROBE-BASED TRAVEL  
SPEED DATA**

A Thesis

by

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## **ABSTRACT**

Standard industry and research practice in the area of transportation system performance measurement utilizes reference travel speed as benchmark for calculation of delay, mobility and reliability indices. These reference speeds reflect free-flow (unconstrained) travel conditions on different facilities (freeways, arterial streets, etc.). However, the rationale behind the choice of this important parameter is still not entirely established. An average driver's perception of reference speed on a roadway segment is influenced not only by the posted limit but also a few other factors including road geometry and driving conditions. Therefore, deriving applicable reference speeds from actual travel time data may be superior to the use of a reference speed value based solely on a fixed posted speed limit. The posted speed limit may not be reflective of current operational conditions on roadway segments.

This research investigates an appropriate reference time window representative of free-flow conditions by analyzing all-day travel patterns. This was done for both uninterrupted flow facilities (interstates and freeways) and interrupted flow facilities (major and minor urban arterials) because of their inherent differences in travel behavior and characteristics. Using probe-based travel time data from INRIX<sup>®</sup>, a private sector data provider, the analysis incorporated different urban areas in order to provide a more balanced representation of travel patterns and minimize any sampling bias.

It is found that nighttime hours provide a good representation of unconstrained travel and reference speed on both interrupted and uninterrupted flow facilities excluding

minor arterial streets. Various temporal windows are examined and based on data availability and variability considerations, the 85<sup>th</sup> percentile speed during 9PM-6AM overnight hours is recommended as reference speed on all uninterrupted flow facilities and major arterial streets. On facilities with sparse traffic and inadequate data during these nighttime hours, mid-day (11AM-4PM) data should be used in place of nighttime hours to derive reference speed. On minor arterial streets, occurrences of actuation and priority treatment cause nighttime hours to concede lower travel speeds and for such facilities, the 85<sup>th</sup> percentile of mid-day (11AM-4PM) data is better representative of reference travel conditions. Inclusion of weekend travel data does not significantly impact derived reference speeds.

## **DEDICATION**

*My parents, teachers, friends and belief*

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# CHAPTER I

## INTRODUCTION

The Moving Ahead for Progress in the 21<sup>st</sup> Century Act (MAP-21) propelled transportation system performance measurement to the center-stage within the transportation profession (1,2). Several state departments of transportation (DOTs), public and private agencies, and metropolitan planning organizations (MPOs) have developed measures and techniques to actively evaluate and address their roadway infrastructure's ability to meet planned objectives. This includes tracking performance, identifying bottlenecks, addressing problem areas and informing decision-making activities.

### **Background**

Among the several approaches targeted toward overall transportation system performance evaluation, one of the more popular and commonly implemented is the measurement of a system's mobility and reliability performance. While mobility measures indicate average travel conditions compared to a reference (usually free-flow) travel condition, reliability measures evaluate the worst travel conditions compared to reference (3). This can vary from the worst 5 percent to worst 20 percent of travel conditions. Industry-wide practice in these areas utilizes a reference travel time for calculation of delay, mobility and reliability indices (3,4). For example,

$$\text{Travel Delay} = \text{Actual travel time} - \text{Reference travel time} \quad (1)$$

$$\text{Travel Time Index} = \frac{\text{Average travel time}}{\text{Reference travel time}} \quad (2)$$

$$\text{Planning Time Index} = \frac{95\text{th percentile travel time}}{\text{Reference travel time}} \quad (3)$$

It is worth recalling at this point that travel time and speed have complimentary relationships in terms of percentiles. For example, 95<sup>th</sup> percentile travel time corresponds to the 5<sup>th</sup> percentile travel speed and vice-versa. Reference speeds typically reflect free-flow (unconstrained) travel conditions on roadways. As seen in equations 1 through 3, the choice of the reference travel time on any facility can affect the ability of the corresponding measures to accurately represent actual system performance. Typically, if the reference speed adopted for measurement is lower than field-observed value, it will underestimate delay, mobility and reliability measures. On the contrary, if the adopted reference speed is higher than actual field value, reported measures will be overestimated. In both cases, the agency will be unable to capture real traveler experience while evaluating performance. Depending on the magnitude of difference in actual and adopted reference values, the reported measures can mis-approximate mobility measures by 20 to 25 percent and even higher for reliability measures (5).

Opinions and practice regarding the choice of reference speed vary among states and agencies. While some adopt the posted speed limit (PSL) on a facility as its reference speed based on the rationale that this is the legal upper limit on how fast drivers can travel on that facility, others prefer to use posted limit plus five mph speed as the reference speed. The latter is based on the rationale that during unconstrained hours, when the traffic is light, drivers are free to travel at a speed they feel is reasonable while

still remaining within legal bounds. Most travelers tend to go just over the speed limit which allows them to travel slightly faster while still staying within allowable range not usually ticketed. Because free-flow speed is not attainable during the major part of a typical day, some agencies use maximum throughput speeds to calculate mobility measures like area- or state-wide vehicle hours of delay (6). The maximum throughput speeds are usually between 70 to 85 percent of PSL and realized when the greatest number of vehicles occupy the highway at a time. Because efficient performance measurement can use rich real-world data, some other agencies prefer to derive reference speeds directly from their available data sets. This allows the data to minimize the potential effects of an arbitrary choice of reference speeds.

The current research is motivated by the lack of standard practice in this area of performance measurement. The study focuses on developing a sound methodology to identify reference speeds working with real-world data from a wide range of metropolitan areas.

### **Research Statement and Objectives**

Using a fixed value such as the posted speed limit as the reference speed can have some limitations. The free-flow speed, as perceived by travelers, is influenced by the posted limit plus a few other factors such as road geometry and driving conditions. For example, travelers may be comfortable traveling faster than the PSL during unconstrained hours on a segment of roadway with standard 12 foot lanes, good sight distances and other favorable travel conditions. But they may travel at a slightly lower

speed (closer to the PSL) on segments of the same roadway with less favorable conditions (narrow lanes, lower sight distances, poor visibility, etc.) during the same unconstrained hours. In essence, different segments of the same roadway with the same posted speed limit may have different reference speeds depending on their geometric and operational characteristics.

Identifying applicable reference speeds for different segments of roadways based on actual travel speed data can be useful. This will enable better reflection of operating conditions on various sections without generalizing conditions over all road sections of a roadway which has been assigned an arbitrary reference value. The National Cooperative Highway Research Program (NCHRP) report 618 recommends evaluating such operational considerations while determining the appropriate reference speed for delay and index computations (7).

For the Urban Mobility Scorecard (UMS) (3) published by the Texas A&M Transportation Institute (TTI), travel time data from private sector data provider INRIX are used. For this application, reference speeds are recalculated each year so that they correspond to the average speed data from INRIX for that data year. This recalculation is performed by INRIX and the values are provided to TTI. This research study focuses on investigating a reliable methodology for this exercise which can have broader applications in the area of transportation system performance measurement and evaluation

For this purpose, there is a need to investigate a reasonable time window of unconstrained travel by analyzing different candidate temporal combinations

representative of free-flow or reference speeds. This has been done for both uninterrupted facilities (freeways) and interrupted facilities (urban arterial streets). These data analyses have been performed separately because of inherent differences in travel behavior and characteristics on these two broad classes of roadway facilities. As an example, the unconstrained night hours (i.e., midnight to 5 AM) can be expected to provide a good representation of free-flow travel on freeway facilities. However, for arterial streets this may not hold in all cases, especially minor arterial streets, because the travel on such facilities is affected by multiple factors, such as signal timing scheme, type of signal actuation adopted during late nighttime periods, etc.

For both interrupted and uninterrupted flow facilities, unconstrained travel is experienced more often during light traffic nighttime hours compared to daytime hours. All day travel patterns have been examined to confirm this phenomenon, and unconstrained nighttime hours (e.g., midnight to 5 AM) are found to serve as a good start point. However, based on availability of data for these light traffic hours, the chosen time window may need to be expanded. This situation is usually encountered in case of arterial streets in urban areas with lower population because they may not have adequate traffic (data points) during the traditional unconstrained night hours to estimate the reference speed. To account for this scarcity, expanding the data window to include a wider range of observations (e.g., 9 PM to 5 AM) may be required. These are just a few of the potential aspects and alternatives which have been investigated in this research.

The analysis incorporates data from different urban areas. This provides a more balanced representation of travel patterns from different composition of driver

population and minimize any sampling bias. Potential effects of urban area size, population and demographic characteristics can therefore be investigated.

### **Thesis Organization**

This thesis is organized into five chapters. Chapter I presents some relevant background, the research problem statement and objectives of this research. Historical and contemporary developments in the area of transportation system performance measurement are discussed in Chapter II. This chapter also introduces how reference speed is defined and provides some context for the current state-of-practice in use of reference speed among various states and agencies in the United States. Chapter III describes the data used in this study and also the data analysis method followed in the later sections. Different aspects of data analysis and interpretation such as various tests for statistical significance of several factors, checks for type of data distribution, effects of adopting identified temporal windows of one facility for another etc. are discussed in detail in Chapter IV. This chapter also discusses the rationale for the selection of appropriate percentile measures to define reference speed. Finally, Chapter V presents a summary of this research and provides recommendations.



## **CHAPTER II**

### **LITERATURE REVIEW**

To begin, researchers conducted a review of the current state-of-practice in the use of reference speeds for performance measurement and the adoption of different alternatives as a measure for reference speed. This helps understand the rationale behind adoption of different proxies for estimation of the same measure and provides direction for the current research. There has been increased research activity in this specific area of performance measurement in recent years. A review of current literature also brings forth the utility of this study in providing a basis for future industry and research implementation.

#### **Developments in Transportation System Performance Measurement**

Performance measurement in the area of transportation system mobility and reliability has gained momentum over the last few years with realization of challenges in transportation funding. The need to prioritize surface transportation funding among competing projects has been recognized and measures have been implemented by planning organizations. In the United States, the Moving Ahead for Progress in the 21<sup>st</sup> Century Act (MAP-21) passed in 2012 provides a performance-oriented basis for surface transportation programs. Different requirements such as performance measurement and evaluation, target-setting and performance reporting etc. have been established under the MAP-21 Congestion Mitigation and Air Quality Improvement program (CMAQ) (1,2).

A common evaluation practice is to measure system performance with respect to a benchmark set as per the concerned decision maker's priorities. For mobility and reliability performance measurement, this benchmark is usually the free-flow travel time (speed) as shown in equations 1 through 3. This reference speed is also referred to as uncongested speed, free-flow speed, unconstrained speed, etc. in other terminology. Essentially, all these are representative of travel conditions in which the driver has complete freedom of choice of travel speed as long as that speed is allowable on the facility, without interference from other users of the facility.

### **Definition of Reference Speed**

The choice of reference speed for performance measurement is not uniform among states and agencies in the United States. Different agencies adopt different proxies to assign reference speeds to their facilities. The Highway Capacity Manual (HCM) (8) defines free-flow speed (FFS) as:

- “The theoretical speed when the density and flow rate on a study segment are both zero.
- The prevailing speed on freeways at flow rates between 0 and 1,000 passenger cars per hour per lane (pc/h/ln). (HCM 2010, pg. 9-8)
- In the context of urban streets, free-flow speed is “...the average running (midblock) speed of through automobiles under low-volume conditions and not delayed by traffic control devices or other vehicles.” (HCM 2010, pg. 17-32)

- For arterial street segments, the base free-flow speed “includes the influence of speed limit, access point density, median type, and curb presence” and is calculated using adjustment factors for cross-section and access points as shown in equation 4.

$$S_{fo} = S_o + f_{cs} + f_A \quad (4)$$

where,  $S_{fo}$  = base free-flow speed

$S_o$  = speed constant

$f_{cs}$  = adjustment for cross-section

$f_A$  = adjustment for access points

The speed constant  $S_o$  is a linear function of the posted speed limit on the segment. It is also indicated that shorter segments have slower free-flow speed. Therefore, the HCM recommends a signal spacing adjustment factor to account for this after calculating  $S_{fo}$  (HCM 2010, pg. 17-33).

The Texas A&M Transportation Institute defines FFS as “the average speed that can be accommodated under relatively low traffic volumes (i.e., no vehicle interactions) on a uniform roadway segment under prevailing roadway and traffic conditions.” While *free-flow speed* is the term used on uninterrupted facilities, *uncongested speed* is the corollary on interrupted-flow facilities.

In line with the HCM definition of *free-flow speed*, TTI has adopted the term *uncongested speed* in the context of arterial streets to mean the “...average speed that can be accommodated under relatively low traffic volumes (i.e., no vehicle interactions) on a uniform roadway segment under prevailing roadway and traffic conditions.”

However, as opposed to the HCM, this definition includes the prevailing traffic signal control delay that occurs in light traffic (9).

Florida DOT defines FFS as the field-measured average speed under low volume conditions, when drivers are not constrained by other vehicles, roadway geometry or traffic control. “In absence of field data, FFS can be estimated at five mph above the posted speed limit.” (10)

### **State-of-Practice in Use of Reference Speed**

Some agencies, cities and MPOs adopt the posted speed limit or posted limit plus five mph speed as reference speed for their use (5-6,11-19). Table 1 provides examples which show the current use of different proxies for reference speed in the United States.

**Table 1: Different Measures of Reference Speed Adopted by U.S. Agencies/ States**

Measure used as Reference Speed	State/ Agency/ MPO
Posted speed limit	MO, NE, NV, OH (defines free-flow as at or near posted limit), VA, WI, WS
Posted limit plus five	OR, FL
Free-flow speed*	CA, MD, Chicago (CMAP)**, New York (NYMTC), TX

*\*the term is not specified in a numerical or temporal boundary definition*

*\*\*Chicago Metropolitan Agency for Planning (CMAP) measures free-flow travel speed based on average travel speeds between 8:00 PM and 5:30 AM (18)*

A recent study was conducted in this research area by the Oregon Department of Transportation using archived travel time data from the National Performance Measurement Research Dataset (NPMRDS) (5). The primary purpose of the study was to identify a good measure for the free-flow or reference speed. The other objective was to identify days of the week which provide a good representation of typical congestion and travel conditions. The roadway studied under this project (OR-217) is similar in characteristics to an urban freeway with limited access control and has a posted speed limit of 55 mph. Data were analyzed at several temporal levels (daily, monthly, yearly aggregation levels) to identify patterns in traffic. After considering various possibilities, the study recommended the use of posted limit plus five mph speed as the reference speed for daily travel, mobility and reliability measures. It also concluded that using data for mid-week time window (Tuesday through Thursday) was better because Monday and Friday showed lower variation in travel times when averaged over a year. The study indicated that this might have been caused because of people working flexible four-day-work-week schedules. Many paid holidays also occurred on Mondays and Fridays, resulting in lower traffic and congestion on these weekdays when averaged over a year.

Although the above study highlights some useful and interesting points, the use of posted limit plus a standard value for all segments of all roadways has scope for improvement. The study analyzed only a limited number of segments on the entire stretch of the 7 mile long roadway. The recommended measure may work reasonably well for relatively small number of segments of a moderately long roadway, but may be unable to provide accurate measures for longer roadways with higher number of

segments. The recommended measures should also account for the effect of length of segments. It is usually observed that shorter segments have lower reference (free-flow) speeds (8). This can be because on shorter arterial segments, where signal spacing is relatively low, vehicles need to accelerate and decelerate more often, and therefore are unable to achieve as high running speeds as on longer segments where they can travel uninterrupted for longer distances.

As discussed previously, changes in operational characteristics result in changes in reference speeds on different segments of a roadway with the same posted speed limit. For this reason, adopting a common reference speed may not provide a good representation of the operational characteristics on all segments of the roadway, particularly when there are a large number of segments. When aggregated at an urban area level, this choice of reference can result in significant differences in reported travel performance measures. Moreover, the choice of excluding Mondays and Fridays from analysis needs further investigation. Because mobility and delay measures are “average” measures, they should represent average traveler experiences, and therefore should account for both low and high delay situations. Excluding the first and last days of the regular work week from analysis procedures does not represent overall average traveler experiences to the full extent.

A recent report on freight performance measurement approaches published by the Federal Highway Administration recommends using the 85<sup>th</sup> percentile of vehicle speeds from the unconstrained travel window as the reference speed (20). The report documents that the 85<sup>th</sup> percentile is a popular choice, however, no specific reason for

this choice was mentioned. These reference speeds should be calculated for each segment of the facility. The reference travel time can be obtained as the segment length divided by the reference travel speed. These reference travel times are then summed together to get the reference travel time for the facility. It is notable that the 85<sup>th</sup> percentile travel speed corresponds to the 15<sup>th</sup> percentile travel time. Therefore, this approach assumes a small amount of delay built into the reference speed. This is reasonable for arterial streets because of a small amount of inherent delay caused due to signal operation, even under low traffic conditions.

There is a general consensus on the use of 85<sup>th</sup> percentile nighttime speed for freeway facilities as reference speed (9,20,21), but practice regarding choice of time window and speed percentile for arterial street facilities varies widely. A few research studies (21,22) have studied the appropriateness of using different percentile values of travel speed for accurate representation of performance metrics on arterial streets. It is suggested by these studies that using the 85<sup>th</sup> percentile of nighttime speeds or even all-day speeds doesn't provide the best possible picture of prevalent delay conditions. One of these studies recommends using the 60<sup>th</sup> percentile of all-day travel speeds based on the observation that 85<sup>th</sup> percentile speed usually falls in the nighttime hours and tends to show higher delay and overestimate congestion on arterial streets (22). The other study suggests using 85<sup>th</sup> percentile of daytime hour (6 AM-8 PM) speed data instead of the all-day data (21).

Signal timing on arterial streets is usually designed to allow fewer interruptions and stoppages on major streets during nighttime light traffic conditions. This allows for

higher speeds during such periods compared to daytime when both (major and minor) streets are given proportional green times. Therefore reference speeds derived from 85<sup>th</sup> percentile nighttime speeds on major arterial streets can overestimate congestion during daytime. Because congestion is mostly a daytime problem, both these studies base their recommendations on the idea that signal timing scheme changes from daytime to nighttime periods, and nighttime speeds can be much higher than daytime speeds. That is why they recommended the use of lower percentiles as discussed earlier.



## **CHAPTER III**

### **STUDY METHODOLOGY**

There is a lack of general agreement on what delay measurement intends to report and the benchmark used for it, therefore, this study investigates what the “free-flow” speed on a facility is, instead of setting a threshold for “reasonable expectancy,” and defining reference speed accordingly. In essence, this study will focus on finding a reference speed that can be achieved on a facility with all favorable conditions rather than limiting reference speed within a “level-of-expectation” boundary. This will enable more consistency in performance measurement reporting activities as the benchmark is set at an absolute scale and not a relative one defined by the user or agency. Moreover, this definition can still be adapted by the concerned user as per the intended objectives if and when deemed necessary.

This research uses all travel time data rather than capping travel time values based on speed limits. This chapter and the following sections summarize the steps involved in achieving the objectives of this research.

#### **Description of Data**

Traffic Message Channel (TMC) is the industry standard nomenclature and spatial reporting unit of measurement used by traveler information providers to define the roadway system. The data for this study come from the INRIX<sup>®</sup> XD<sup>™</sup> database. The XD segments, as denoted by INRIX, are similar in nature to TMCs but typically are shorter

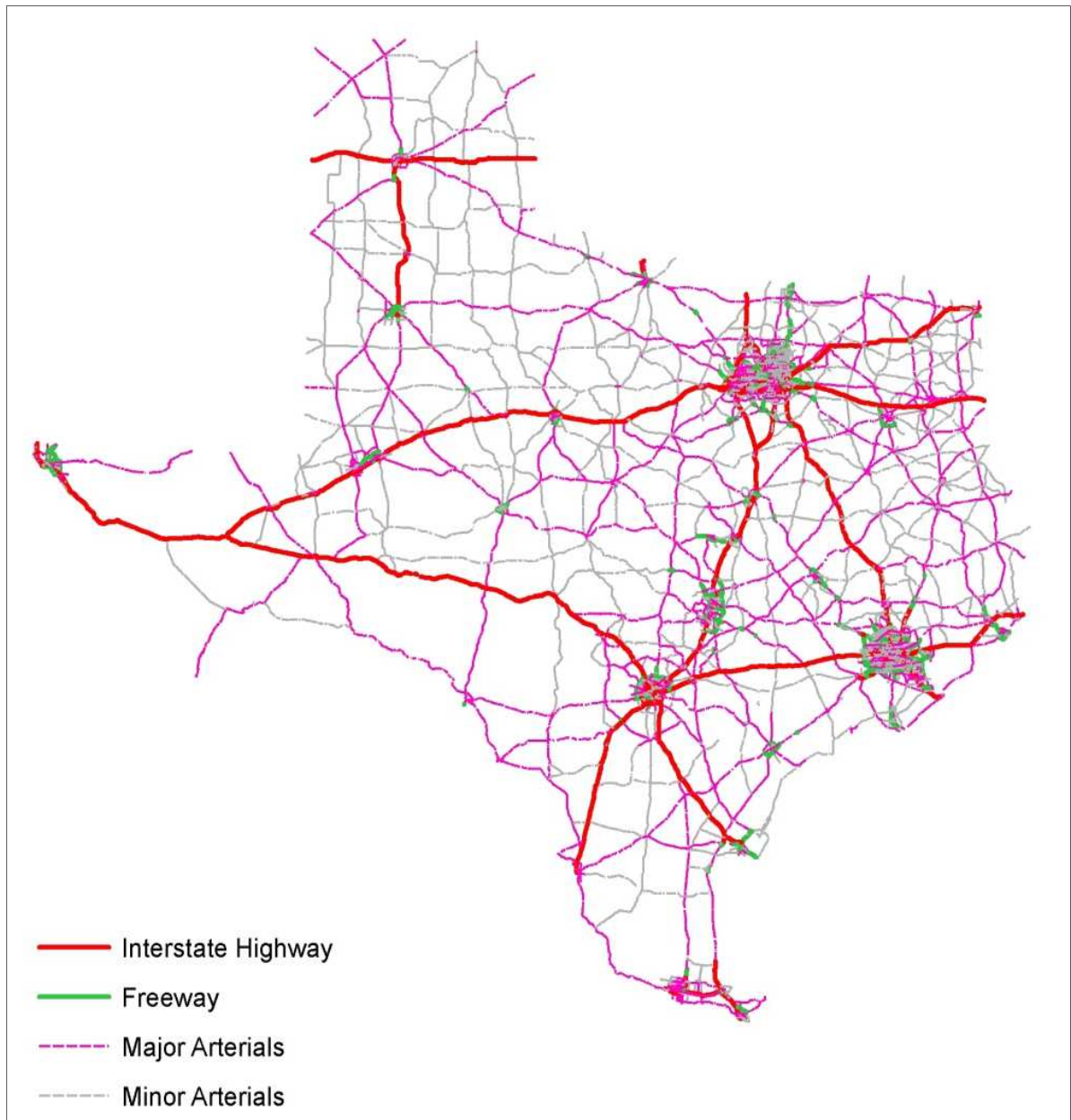
and have higher spatial resolution (up to 250 meters on major roads) compared to typical TMC resolutions of 1-3 miles. For the available dataset, these XD segments are typically 1 mile or less in length. The dataset used in this study consists of travel time data for the calendar year 2014 from several urban areas in Texas with a few suburban and rural areas also included. The database consists of 10,584 freeway XD segments and 17,057 arterial segments. Table 2 provides details on road mileage for different facility types in some of the major urban areas incorporated in this study. These urban areas are listed in order of total road mileage of all segments on which travel time data is available.

**Table 2: Segment Mileage for Each Road Functional Class in Urban Areas Studied**

Urban Area	Total Segment Length (miles)		
	Freeway/Interstate	Major Arterial	Minor Arterial
Dallas-Ft Worth-Arlington	667.5	733.5	517.2
Houston	508.8	631.5	656.8
San Antonio	260.6	220.3	193.2
Austin	182.8	256.1	115.4
El Paso	97.6	156.4	9.8
McAllen	11.9	164.5	41.3
Denton-Lewisville	41.9	71.7	36.6
Amarillo	32.2	58.0	33.2
Waco	38.9	53.6	19.4
Lubbock	55.5	41.7	7.1
Odessa	29.0	64.7	9.8
Corpus Christi	55.0	27.3	11.6
Tyler	0.4	88.9	4.6
Beaumont	37.2	38.9	15.9
Abilene	21.7	54.8	14.0
College Station-Bryan	20.1	50.8	16.7
Victoria	24.9	39.8	20.1
Brownsville	22.0	51.9	10.5
Temple	22.8	43.4	8.6
Midland	35.5	31.8	5.8
San Angelo	13.4	21.1	37.0
McKinney	16.6	43.6	10.5
Killeen	21.9	35.4	12.0
Wichita Falls	26.9	41.1	-
Longview	6.5	58.6	2.2
Sherman	23.4	15.3	28.4
Texarkana	15.2	30.1	10.2
Harlingen	19.9	24.1	10.6
Texas City	20.8	26.3	-
Laredo	10.4	29.5	0.7
Port Arthur	16.4	15.0	4.2
Lake Jackson-Angleton	3.1	-	-

*Note: “-” indicates that no data were recorded or available for any segments of corresponding facility type*

Figure 1 shows the roadways for all four facility types (interstates, freeways, major and minor arterials) used in this study on the state map of Texas.



**Figure 1 Texas state map showing all roadway segments used in the study**

INRIX provides annual average travel times for each 15-minute interval of each day of the week. For example, a data entry for 01:15 AM on Monday provides the annual average travel time of all vehicles traveling on that segment between 01:15 AM and 01:30 AM. This equates to 672 “cells” of travel time data (24 hours per day\*4 fifteen-minute intervals per hour\*7 days per week) for each XD segment. These travel times have been collected using vehicle probe technique which captures vehicle travel speeds based on cellular and Global Positioning System (GPS) data. The database consists of “point-paired” data which capture the vehicle travel times between detector locations, and not the vehicle spot speeds at individual detector locations on any road segment. In this respect, these data are representative of space mean speed commonly used in transportation studies. The space mean speeds are generally lower than spot speeds because they are calculated over an extended length of segment, and therefore, weigh slower vehicles more effectively compared to spot speeds which assign equal weights to each speed observation. The analysis incorporates data from different urban areas of varying sizes and populations. This will help provide a balanced representation of travel patterns among selected data while minimizing any sampling bias.

Data availability challenges were experienced working with different kinds of roadway segments in this database. Arterial segments are observed to suffer from lack of data to varying extents during traditional unconstrained hours of the day (9PM-6AM). This is observed particularly for rural arterial segments which witness sparse to no traffic during such periods of the day. About 23 percent of arterial segments (3,923 of 17,057) were observed to have less than 50 percent of data available for usual unconstrained

hours (i.e., fewer than 90 of 180 cells filled for the period 9 PM-6 AM on all weekdays). All cells with “zero” entries were set to missing to facilitate consistent calculation of means, standard deviations, percentiles and other statistics. Moreover, for segments with such sparse data, an alternate window for unconstrained travel with higher data availability was investigated. Otherwise the corresponding results can be subject to high fluctuation and may not be dependable. This aspect of data analysis has been discussed in more detail in Chapter IV.

Because this study is based on actual vehicle travel times, inventory data for roadway speed limits will not be required. The 15-minute aggregated travel times have been converted to respective travel speeds for each segment based on its length. Conversion from travel times to speeds makes understanding the data easier and more intuitive without losing any information. The reference speeds on multiple contiguous XD segments can then be used to obtain the reference travel speed on a longer road segment using equation 5.

$$V_{ref,seg} = \frac{\sum_{i=1}^n l_i}{\sum_{i=1}^n \frac{l_i}{V_{i_{ref},XD}}} \quad (5)$$

where,

$V_{ref,seg}$  = reference speed on a longer road segment of interest

$l_i$  = length of individual XD segments constituting the longer road segment

$V_{i_{ref},XD}$  = reference speed on individual XD segments constituting the longer road segment

During the course of this study, the need to expand the time period for night-time unconstrained travel appropriately can arise depending on the number of available data points for those hours. For example, if the traffic is very light on minor urban arterials

during traditional night-time hours, the window may need to be expanded to include hours with slightly higher traffic and data points. Including a few more “normal” operation hours can also help counter effects of semi-actuated operation which generally favors the major street traffic during light traffic hours. During such periods, semi-actuated operation allows major street traffic to flow uninterrupted unless a service call is received from minor street traffic. Because of this, the minor street rarely experiences unconstrained travel in the real sense even during very light traffic periods. Expanding the data window can account for this to an extent because the period between peak hours and truly unconstrained hours is less affected by delay from actuation on minor streets.

### **Analysis Methodology**

Several candidate temporal combinations of travel patterns are investigated to have a more complete understanding of feasible alternatives for selection of reference speeds. This includes preliminary identification of unconstrained travel time intervals on weekdays and weekends for both freeways and arterial streets. It is reasonable to expect that these time windows are different for weekdays and weekends based on observed travel patterns. This exercise guides further investigation based on whether including weekend travel data has a significant influence on reference speeds. Because travel characteristics can be different for the two kinds of facilities, unconstrained hours will be identified for them separately. For comparison, the effect of utilizing the identified travel window of one facility for the other one has also been analyzed. For example, if an unconstrained travel window of 12 AM-5 AM is identified for freeway facilities, this

study investigates if the same window works adequately for arterial facilities as well, and vice-versa.

It is usual for the study to follow slightly different approaches for freeway and arterial street facilities, for reasons discussed in previous sections. However, an investigation regarding use of a single time period which can perform reasonably well for both freeway and arterial facilities has also been performed. The overall focus will consider identifying techniques and time windows which offer a good picture of unconstrained travel irrespective of the type of facility (freeway or arterial). This will help in deriving reference speeds without needing additional information on the type of facility, which can be useful for data analysis purposes.

Tests for statistical difference in means and variance are performed to assess the choice between different candidate windows. For example, if the observed reference speeds from two different time windows are not found to be statistically different (even though they have slightly different values), the time window with the lower variability (shown by standard deviation and coefficient of variation) will be chosen. As explained in Chapter IV, the coefficient of variation (CV) which is the ratio of standard deviation of speeds and the mean speed, has been used as a metric for choosing appropriate reference travel time windows. While selecting a reference travel window, this metric has been limited to a maximum value of 10 percent for both uninterrupted and interrupted flow facilities. Compared to standard deviation, limiting the upper value of coefficient of variation has the advantage of normalizing the effect of mean travel speed. For example, in comparison to a fixed value of standard deviation, CV is better able to



account for the different levels of base speeds that uninterrupted and interrupted flow facilities typically observe.

The sequence of data analysis for identification of unconstrained travel window broadly consists of the following six steps:

- Step 1: Visual inspection of all-day 15-minute average travel speed pattern to identify candidate time windows for each type of transportation facility
- Step 2: Check for data adequacy within identified time windows
- Step 3: Use limitation on higher value of coefficient of variation to select appropriate time windows and eliminate windows with higher variability in travel speeds
- Step 4: Select time window with lower variability if alternate windows have statistically indifferent reference speeds
- Step 5: Investigate data distribution and choice of appropriate percentile to define reference speed within identified time windows
- Step 6: Examine statistical significance of effects of using common time windows for all types of facilities, utility of including travel data from weekends along with regular workweek travel data

## **CHAPTER IV**

### **DATA ANALYSIS AND RESULTS**

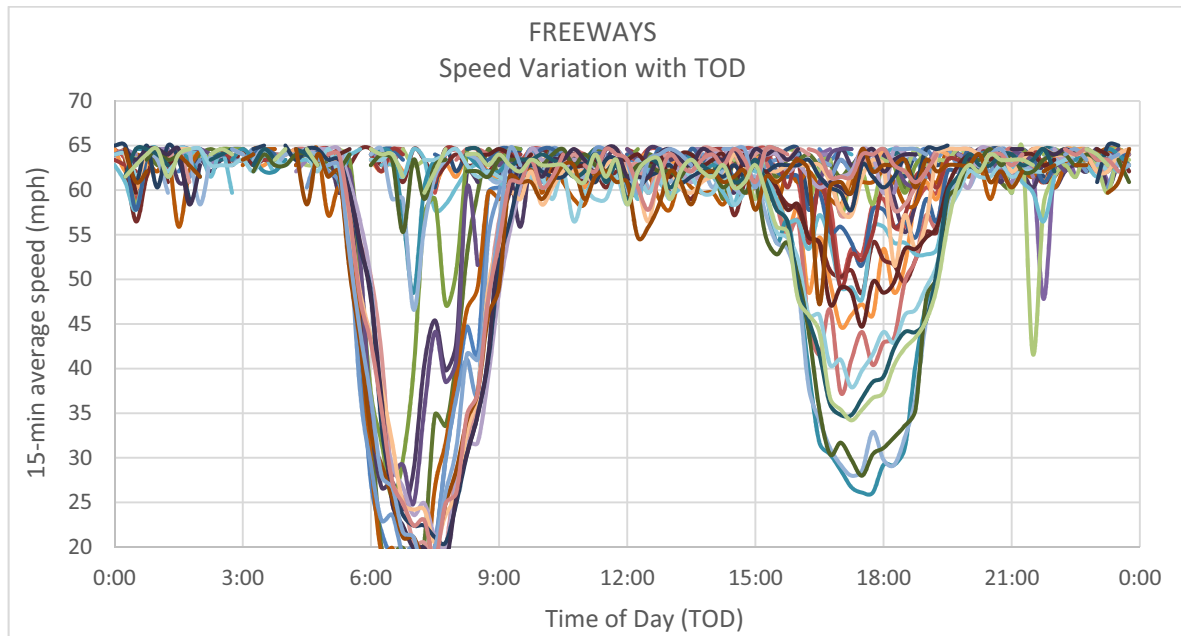
This chapter describes the steps involved in identifying and selecting appropriate unconstrained travel windows and then the associated reference speeds. These steps are presented sequentially for both uninterrupted flow facilities and interrupted flow facilities to enable better comprehension.

#### **Visual Inspection of All-Day Travel Patterns**

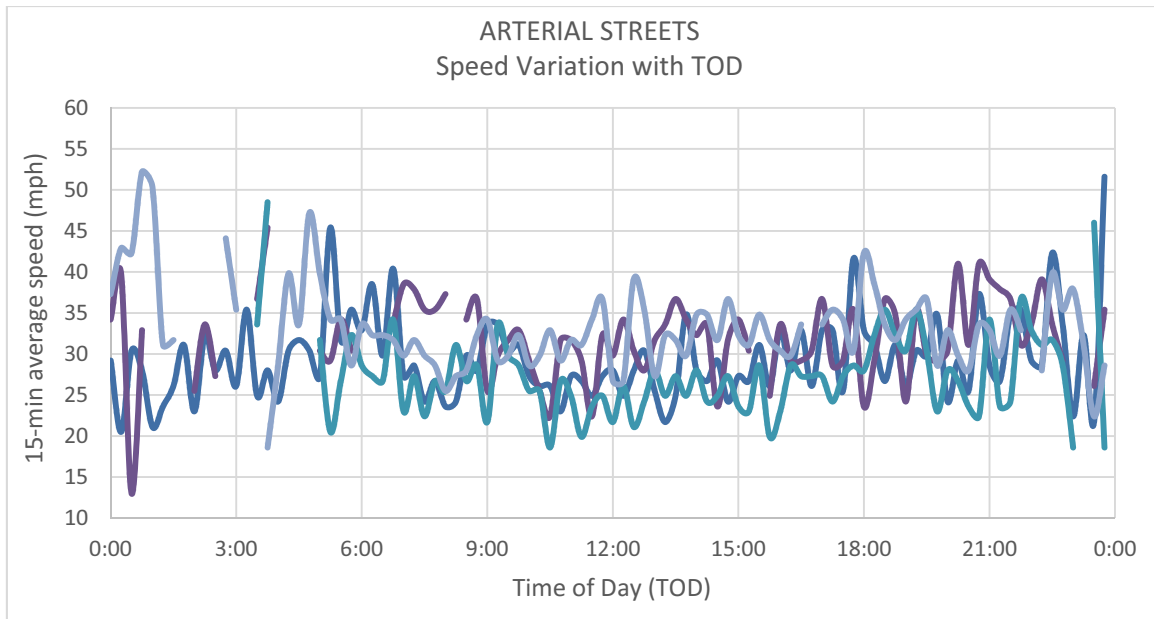
The preliminary step in narrowing candidate travel windows with speeds potentially close to the facility's reference speed is visually inspecting travel speed patterns for all-day travel. This gives an estimate of smaller temporal windows that can be investigated further. This exercise was performed for all uninterrupted and interrupted flow facilities included under this study. Figure 2 and Figure 3 show typical all-day travel speed patterns for a few freeway and arterial street facilities respectively. Each line represents annual average 15-minute travel speeds throughout the day on one segment (freeway segment in Figure 2 and arterial street segment in Figure 3). It should be noted that the speed patterns shown are line graphs instead of point scatter plots just for ease of observation. It is understood that because of 15-minute aggregation, the data are not continuous in the true sense, which the line graphs may suggest.

Barring minor variations caused by local conditions and data collection limitations, both types of facilities showed very similar travel patterns within their

respective type. However, these patterns showed some dissimilarities also between the two types. As seen in Figure 2, freeway facilities tend to show significantly lower speeds with onset of peak period congestion during morning and evening peaks. Although the observation is on similar lines for interrupted flow facilities (Figure 3), the magnitude of drop in speed during peak periods is relatively lower.



**Figure 2 Travel speed variation with time of day for freeway facilities**



**Figure 3 Travel speed variation with time of day for arterial street facilities**

For freeways, two candidate time windows for unconstrained travel were identified. The first was 2 AM-5 AM and the second one was 11 PM-5 AM. One consideration while expanding the window from a three-hour window (2 AM-5 AM) to a six-hour window (11 PM-5 AM) was adequacy of data within the selected time window. Because the analysis uses 15-minute data aggregation level, each additional hour contributes four data points. However, moving away from the most preferred unconstrained travel speed window (2 AM-5 AM in this case) can induce higher variability in data if significant speed drops or rises are observed outside this window. Therefore, a decision has to be made keeping in mind a balance between data adequacy

and variability. The next section discusses this in more detail and provides bases for selection between alternate travel windows.

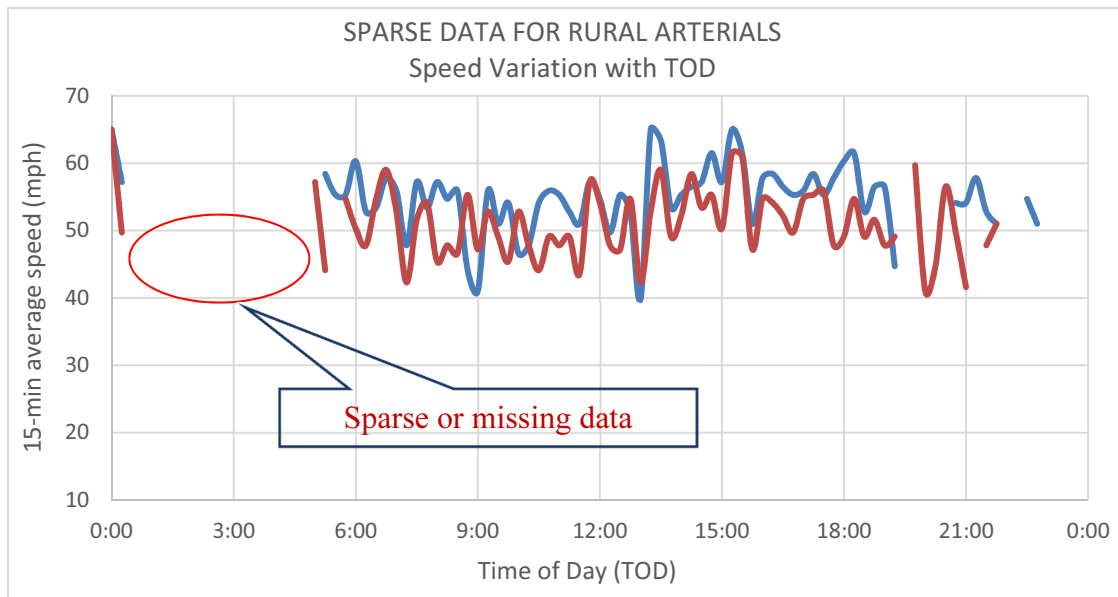
For interrupted flow facilities, 9 PM-6 AM was identified as the preferred window for unconstrained travel. This was also decided based on data inadequacy during traditional unconstrained hours (11 PM-5 AM) for some arterial streets as shown in Table 3. This table provides details on average data availability (average percentage of cells filled out of 180 cells (for 9PM-6AM) or 120 cells (for 11PM-5AM)) for different facility types during the two unconstrained travel windows under consideration.

**Table 3: Average Percentage Data Availability for Different Facility Types During Unconstrained Travel Windows**

Facility Type		Percentage Data Availability Within Specified Time Window (percentage)	
		11 PM – 5 AM	9 PM – 6 AM
Uninterrupted Flow	Interstate	91.8	96.2
	Freeway	79.5	86.9
Interrupted Flow	Major Arterial	66.1	78.1
	Minor Arterial	56.8	65.2

Even within an expanded window of 9 PM-6 AM, a proportion of arterial streets did not have sufficient data to draw useful inferences. Figure 4 shows typical travel pattern for such arterial streets. As discussed in Chapter III (section for data description),

about 23 percent of arterial segments (3,923 of 17,057) had less than 50 percent of 180 cells of data filled for the period 9 PM-6 AM. This is observed particularly for rural arterial (minor street) segments.



**Figure 4 Travel speed variation for arterial street facilities having sparse data**

For such facilities, an alternate mid-day time window was required because conclusions based on very sparse data can be subject to high fluctuations and may not be dependable for sustained performance measurement. This was determined to be 11 AM-4 PM for which the next section provides more details in terms of data availability and variability within the time window.

## **Determination of Appropriate Time Windows: Selection between Candidate Windows**

Travel speeds can achieve high values during different parts of the day, however, it is difficult and impractical to assign several distinct and spaced out travel time windows as reference travel windows. Also, although a relatively high average speed may be observed during a few 15-minute windows in a short period of time, it is not very meaningful to consider such spikes in speeds if these speeds cannot be maintained over a longer period of time. Therefore, it is necessary to find a balance between the magnitude of average 15-minute travel speeds and their consistency over a reasonable duration. In other words, both the value of reference speed as well the average speeds' variability need to be considered.

As a result, the all-day travel patterns were observed in conjunction with the coefficient of variation of average travel speeds. The coefficient of variation, CV, is the ratio of standard deviation ( $\sigma$ ) and the mean ( $\mu$ ).

$$CV = \frac{\sigma}{\mu} \quad (5)$$

For the purpose of this study, mean travel speed was calculated on each segment for different periods of the day along with the standard deviation of the speeds for the same time periods. For example, if the mean speed was calculated on a segment for the duration 6 AM-10 AM on all weekdays (average of 80 cell values [4 hours\*4 fifteen-min intervals per hour\*5 weekdays]), the standard deviation of speeds for the same time period was also computed to obtain the coefficient of variation for the time period. After

obtaining these values for all visually appealing time windows, the coefficient of variation (defined in terms of travel speed in our case) was limited to a maximum value of 10 percent for determining the candidate reference travel time windows. Based on the values of mean and 85<sup>th</sup> percentile travel speeds, various unconstrained travel time windows were investigated. As shown in Table 4, these time windows are slightly different depending on the type of transportation facility. The final unconstrained time windows were obtained from the listed options based on variability in values (indicated by coefficient of variation). Any time windows with coefficient of variation greater than 10 percent were not carried forward into the analysis stage because of high fluctuation in their speed values which may result in potentially highly variable (unstable) reference speed. Although such a reference speed can reflect actual field conditions in some cases, it may not be dependable for performance measurement activities in all cases because of high variability.

**Table 4: Unconstrained Travel Windows for Different Facility Types**

Facility Type		Candidate Time Windows for Unconstrained Travel	
		Daytime Window(s)	Nighttime Window(s)
Uninterrupted Flow	Interstate and Freeway	9 AM-11 AM, 1 PM-3 PM	7 PM-9 PM, 10 PM-6 AM, 2 AM-5 AM
Interrupted Flow	Major Arterial	10 AM-1 PM, 2 PM-4 PM	9 PM-6 AM
	Minor Arterial	8 AM-10 AM, 11 AM-4 PM	10 AM-12 AM, 2 AM-6 AM



The coefficient of variation was preferred as a metric over standard deviation by itself because CV accounts for the effect of varying reference speeds on different types of segments and facilities. CV normalizes the variability in speeds with respect to the mean speed. For example, while a freeway facility can have a reference speed of 60 mph, an arterial facility can have it as 40 mph, and the coefficient of variation is able to account for these different levels of base speeds better than a fixed value of standard deviation. Considering all roadway segments, the mean coefficient of variation was found to be 5 percent for uninterrupted flow facilities during the chosen reference travel time window (9PM-6AM) while it was 8 percent for interrupted flow facilities.

#### **Use of Weekend Travel Data Along With Weekday Travel Data**

Including weekend travel data along with regular weekday data was investigated. Similar to the case of choice in reference speed metric, there is no common standard among agencies for the use of weekend travel data. The statistical significance of including weekend data in this analysis was investigated.

Following a procedure similar to that explained in the previous section with a maximum limit on CV, the reference travel time window during weekends (Saturday and Sunday) was identified as 5 AM-9 AM. This time period was also found to be consistent with current practice of a few agencies which use weekend data to define reference speed (13).

Only a small portion of freeway segments (9.8%) and arterial segments (7.2%) showed marginal increase in values of reference speeds when weekend data were

included. In those cases too, the highest magnitude of increase compared to “weekday-only” data was 1.7 mph and most of them ranged between no increase to an increase of 1 mph. Therefore, one-sided statistical tests for difference of means were done to check if these increases were statistically significant. The following tables show the results for test of statistical significance of including weekend data (Sat-Sun) along with regular work week (Mon-Fri) data. The null hypothesis  $H_0$  is that there is in fact no statistical difference in reference speeds between “weekday-only (Mon-Fri)” and “complete week (Mon-Sun)” data. In the following tables,  $\mu_1$  represents reference speed using work week data while  $\mu_2$  represents reference speed including weekend data (data considering all seven days of the week). For each pair of rows, the second, third and fourth columns show the reference speed, standard deviation and sample size for respective cases (workweek or complete week) on a road segment. The remaining statistics used for the hypothesis test are provided in columns five through seven. Table 5 shows results for freeway segments while Table 6 shows corresponding results for arterial segments.

**Table 5: Results from Two-Sample One-Sided t-tests for Reference Speed Including Weekend Travel on Freeways (Level of Significance,  $\alpha=0.05$ )**

Comparison Case	Ref Speed ( $\mu$ )	Std. Dev. ( $\sigma$ )	No. of Samples (n)*	Alternate Hypothesis ( $H_1$ )	t-stat	t-critical ( $\alpha=0.05$ )	Conclusion
segment 3169716 (work week)	62.4	4.04	178	$\mu_1 < \mu_2$	-0.33	-1.645	H <sub>0</sub> cannot be rejected
segment 3169716 (including weekend)	62.6	4.19	210				
segment 3170586 (work week)	64.0	3.93	173	$\mu_1 < \mu_2$	-1.47	-1.645	H <sub>0</sub> cannot be rejected
segment 3170586 (including weekend)	64.6	3.97	205				
segment 5307723 (work week)	62.1	2.99	109	$\mu_1 < \mu_2$	-1.12	-1.645	H <sub>0</sub> cannot be rejected
segment 5307723 (including weekend)	62.6	3.02	121				
segment 5307877 (work week)	64.3	2.07	178	$\mu_1 < \mu_2$	-0.48	-1.645	H <sub>0</sub> cannot be rejected
segment 5307877 (including weekend)	64.6	2.10	190				
segment 5448740 (work week)	52.2	3.76	180	$\mu_1 < \mu_2$	-1.59	-1.645	H <sub>0</sub> cannot be rejected
segment 5448740 (including weekend)	52.8	3.67	212				

*\*Note: Number of samples (column 4) in the first row of each pair of rows represents samples (filled data cells) out of 180 (5 days x 9 hours x 4 times per hour) and the second row represents samples out of 212 (5 days x 9 hours plus 2 days x 4 hours each 4 times per hour)*

**Table 6: Results from Two-Sample One-Sided t-tests for Reference Speed Including Weekend Travel on Arterial Streets (Level of Significance,  $\alpha=0.05$ )**

Comparison Case	Ref Speed ( $\mu$ )	Std. Dev. ( $\sigma$ )	No. of Samples (n)*	Alternate Hypothesis ( $H_1$ )	t-stat	t-critical ( $\alpha=0.05$ )	Conclusion
segment 3145998 (work week)	37.4	7.21	124	$\mu_1 < \mu_2$	-1.29	-1.645	H <sub>0</sub> cannot be rejected
segment 3145998 (including weekend)	38.5	7.22	144				
segment 3168704 (work week)	44.1	6.07	174	$\mu_1 < \mu_2$	-0.97	-1.645	H <sub>0</sub> cannot be rejected
segment 3168704 (including weekend)	45.7	5.99	204				
segment 3168876 (work week)	32.3	5.76	139	$\mu_1 < \mu_2$	-0.90	-1.645	H <sub>0</sub> cannot be rejected
segment 3168876 (including weekend)	32.9	5.79	166				
segment 3169228 (work week)	27.3	3.62	180	$\mu_1 < \mu_2$	-0.67	-1.645	H <sub>0</sub> cannot be rejected
segment 3169228 (including weekend)	27.6	3.59	212				
segment 3169229 (work week)	19.2	5.22	62	$\mu_1 < \mu_2$	-0.78	-1.645	H <sub>0</sub> cannot be rejected
segment 3169229 (including weekend)	19.9	5.31	73				

*\*Note: Number of samples (column 4) in the first row of each pair of rows represents samples (filled data cells) out of 180 (5 days x 9 hours x 4 times per hour) and the second row represents samples out of 212 (5 days x 9 hours plus 2 days x 4 hours each 4 times per hour)*

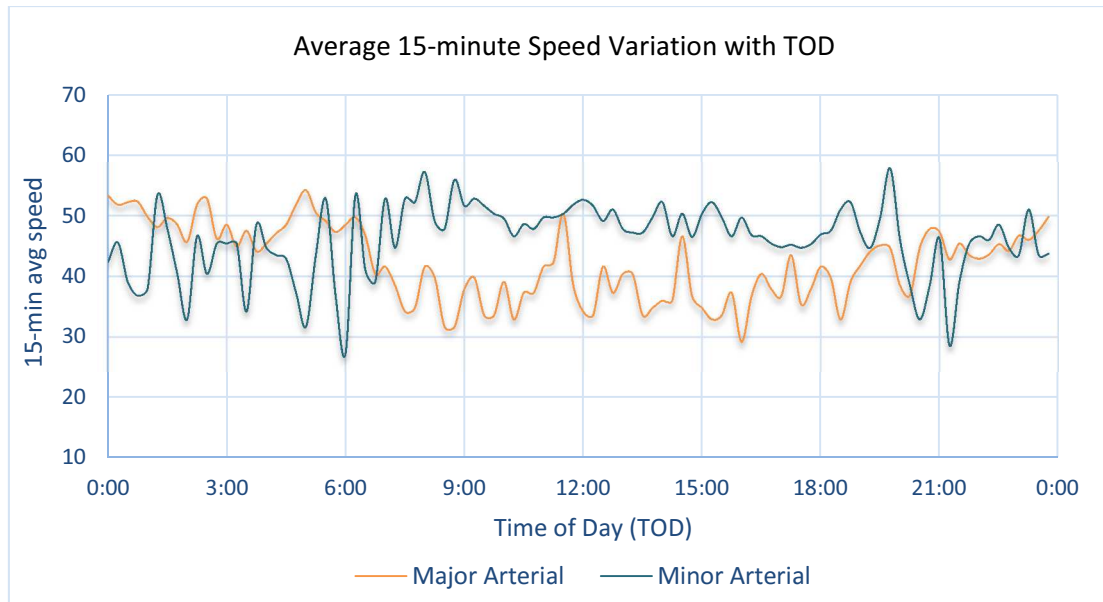
As shown in the tables above, including weekend travel time data rarely changed the reference speed significantly as compared to using only weekday data. For 16,225 of 17,057 arterial segments and for 9,686 of 10,584 freeway segments, including weekend unconstrained travel (5AM-9AM) did not have a statistically significant effect on reference speeds. This shows that for most transportation facilities, as long as the reference travel time windows are chosen appropriately, the reference speed does not change significantly if including weekends. This is intuitive because the travel behavior for a driver familiar with the facility does not change significantly during what are typically low traffic periods and when traffic pressure does not have an effect on driving behavior.

For those facilities which showed statistically significant increase in reference speed when including weekend data as compared to weekday-only data (mostly observed for freeway segments in this study), the effect on delay and other metrics can vary depending on the length of corresponding segments and the volume of traffic they carry. For instance, a longer segment with a higher difference in reference speed and carrying a high traffic volume can have higher differences in magnitude of metrics calculated. This aspect can be explored in future studies.

### **Effect of Type of Arterial Street (Major vs. Minor) on Unconstrained Travel Window**

Within the arterial street facility type, the travel time pattern is different for major and minor arterials. Figure 5 shows the variation of average 15-minute travel speed

throughout a day for major and minor arterial street segments separately. As seen in the figure, the average travel times on all major arterial segments follow a pattern similar to freeways, wherein the overnight period travel times are higher than the rest of the day. However, minor arterial streets follow a slightly different pattern wherein the nighttime travel times are in fact lower than some parts of daytime travel and there is higher variability of average speeds within this time window. This typically happens because traffic on major arterial streets is given priority over minor street traffic. For example, if the signals are actuated, the minor street does not receive a green indication until a call is placed by a vehicle through detection. Even when the signals are pre-timed, the major street receives most part of the green phase, and therefore, minor street vehicles are delayed even when there is light traffic on minor streets. Major street vehicles which are able to get uninterrupted service at minor street intersections are able to register lower travel times (higher average speeds), while those which need to wait for the green indication because of actuation or priority treatment experience a higher travel time. This gives rise to an overall higher fluctuation in travel time as seen in the left portion of graph (12AM – 6AM) for the minor arterial segments.



**Figure 5 Travel speed variation for major and minor arterial street facilities**

Accounting for this difference in characteristics of arterial streets depending on their type is important when determining their reference speeds. Traditional nighttime hours work well for freeways and major arterial streets, but they may not best represent free-flow conditions on minor arterials because of signal timing scheme and actuation factors. Alternatively, a mid-day period of 11 AM-4 PM can be used as time window for determination of reference travel time on minor arterial segments. This time period resulted from the same selection procedure as followed for freeway and major arterial segments whereby candidate time windows were first identified based on visual examination of travel patterns, and then windows with high coefficient of variation

(greater than 10 percent) were removed from further analysis. For minor arterials, the coefficient of variation decreased from 16.4 percent during traditional unconstrained travel period (9 PM-6 AM) to 7.2 percent during mid-day period (11AM-4 PM). This reduction in variability of speed can be seen in Figure 5. Moreover, on average, the 85<sup>th</sup> percentile speed value experienced a slight increase (5.7 percent) for all minor arterial streets going from nighttime to mid-day unconstrained travel period. Adopting this mid-day period for minor arterials results in higher and more consistent speeds, and thus fulfils the creation set for defining reference speeds.

### **Use of a Common Time Window for All Facility Types**

As mentioned in a previous section for typical cases of arterial streets, data adequacy can be a challenge when the travel time window approaches the traditional low traffic nighttime hours. As seen earlier in Table 2, the average data availability percentages for major and minor arterial streets are 66.1 and 56.8 percent respectively. To accommodate for this potential issue, this reference travel window was expanded from 11 PM-5 AM to 9 PM-6 AM. This increases the average data availability to 78.1 and 65.2 percent for major and minor arterial streets respectively.

Statistical tests were performed in order to ensure that this time window expansion did not significantly lower reference speeds calculated on freeway segments. From an ease-of-application point of view, an analysis was performed to check for the statistical effect of using the chosen arterial street reference travel time window for freeway facilities. Table 7 shows the results of t-test conducted to check for effect of



using a common travel time window (9PM-6AM) for freeway facilities on the reference travel speed of freeway. Alternatively, the differences between reference speeds on freeway facilities from two difference time windows (11PM-5AM and 9 PM-6AM) are checked for statistical significance.

**Table 7: Results from Two-Sample Two-Sided t-tests for Reference Speed on Freeway Facilities from Two Alternative Time Windows (Level of Significance,  $\alpha=0.05$ )**

Comparison Case	Ref Speed ( $\mu$ )	Std. Dev. ( $\sigma$ )	No. of Samples (n)*	Alternate Hypothesis ( $H_1$ )	t-stat	t-critical ( $\alpha=0.05$ )	Conclusion
segment 3168724 (11PM-5AM)	64	5.2	109	$\mu_1 \neq \mu_2$	0.875	$\pm 1.645$	$H_0$ cannot be rejected
segment 3168724 (9PM-6AM)	63	5.8	167				
segment 3168725 (11PM-5AM)	52	7.9	111	$\mu_1 \neq \mu_2$	0.576	$\pm 1.645$	$H_0$ cannot be rejected
segment 3168725 (9PM-6AM)	51	8.9	171				
segment 3168946 (11PM-5AM)	64	2.7	113	$\mu_1 \neq \mu_2$	1.195	$\pm 1.645$	$H_0$ cannot be rejected
segment 3168946 (9PM-6AM)	63	2.8	164				
segment 3169114 (11PM-5AM)	58	4.3	120	$\mu_1 \neq \mu_2$	-1.008	$\pm 1.645$	$H_0$ cannot be rejected
segment 3169114 (9PM-6AM)	59	5.5	180				
segment 3169200 (11PM-5AM)	55	9.7	94	$\mu_1 \neq \mu_2$	-0.579	$\pm 1.645$	$H_0$ cannot be rejected
segment 3169200 (9PM-6AM)	56	9.1	110				

*\*Note: Number of samples (column 4) in the first row of each pair of rows represents samples (filled data cells) out of 120 (5 days x 6 hours x 4 times per hour) and the second row represents samples out of 180 (5 days x 9 hours x 4 times per hour)*

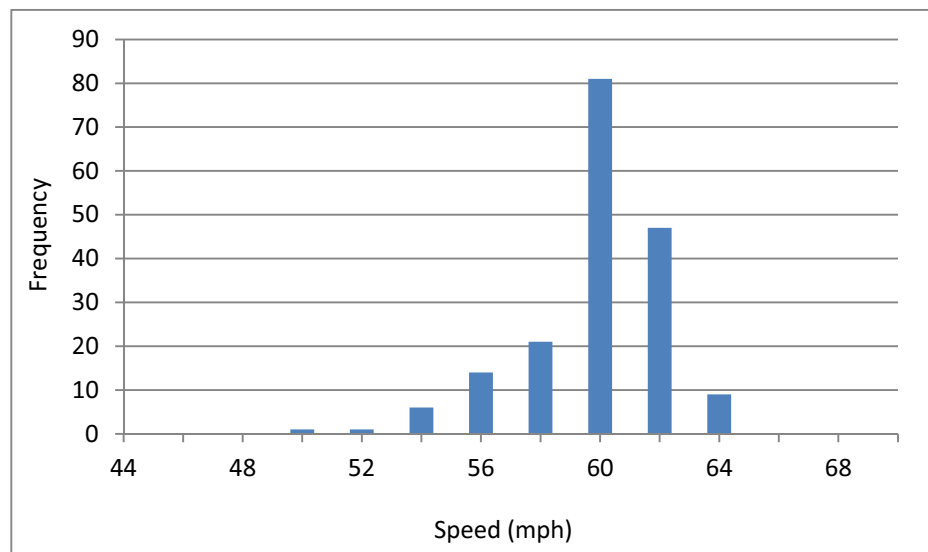
For 9,529 of 10,584 freeway segments, changing from the 11PM-5AM window to 9 PM-6 AM window does not have a statistically significant effect on reference speeds. For the remaining in which the differences were found to be significant, the maximum magnitude of difference was 1.8 mph. This can have an effect on delay and mobility metrics. This effect can vary depending on the length of the segment and the volume of traffic on the segment. For instance, a longer segment with a higher difference in reference speed and carrying a high traffic volume can show higher differences. This aspect is not explored in this research and can be studied in future work.

### **Check for Normality of Data and Selection of Appropriate Percentile to Define Reference Speed**

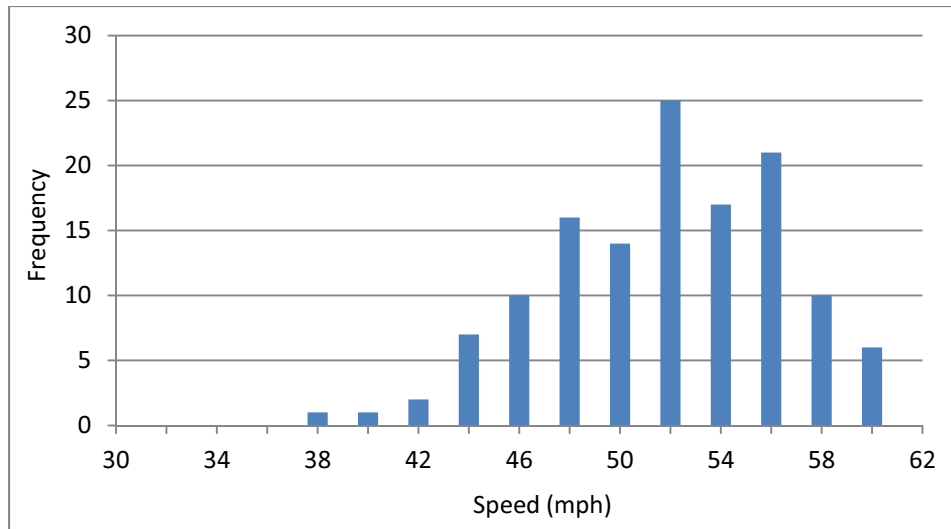
A vast majority of transportation data, particularly traffic speed data, start following a normal distribution as the level of data aggregation increases. With increasing aggregation, the travel time data starts to move from a right skew (a longer right tail) to a more symmetric normal distribution. Contrarily, travel speed distribution moves from a left skew distribution to a normal distribution. This is experienced even more during unconstrained travel windows when vehicles travel at similar speeds and the variability is limited compared to all-day speed variation. A few assumptions regularly used in transportation engineering are based on normal distribution of data. For example, the basis behind using the 85<sup>th</sup> percentile value to assign speed limit on roadways is that the 85<sup>th</sup> percentile captures data within two standard deviations of the mean (and the median

if the data is perfectly normal). A few other related points are discussed in more detail later in this section.

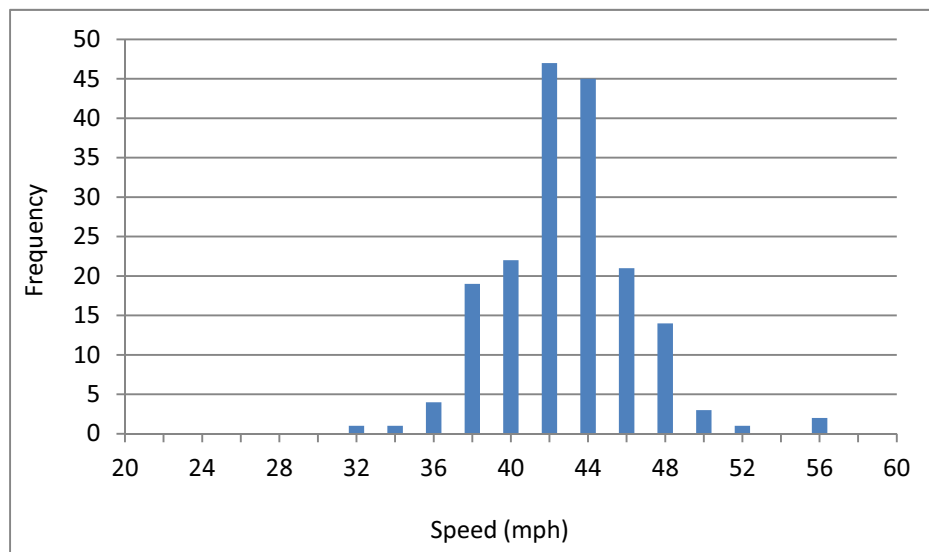
Two of the more popular methods to check for normality of data are the histogram and the cumulative distribution function plots (also called CDF plot). The 15-minute average speed data from preferred unconstrained travel time windows (9 PM-6 AM for freeways and major arterial streets; 11 AM-4 PM for minor arterial streets) were used to obtain their histogram and CDF plots. As seen in Figure 6 through Figure 13, the results indicate that within the chosen reference travel windows, the data follow normal distribution very closely.



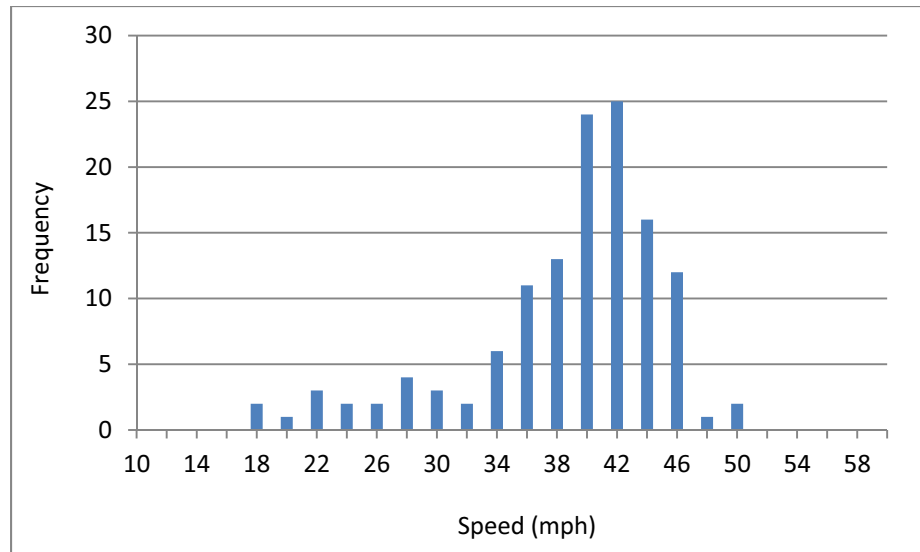
**Figure 6 Histogram of average speeds on an Interstate segment (9PM-6AM, Mon-Fri)**



**Figure 7 Histogram of average speeds on a freeway segment (9PM-6AM, Mon-Fri)**

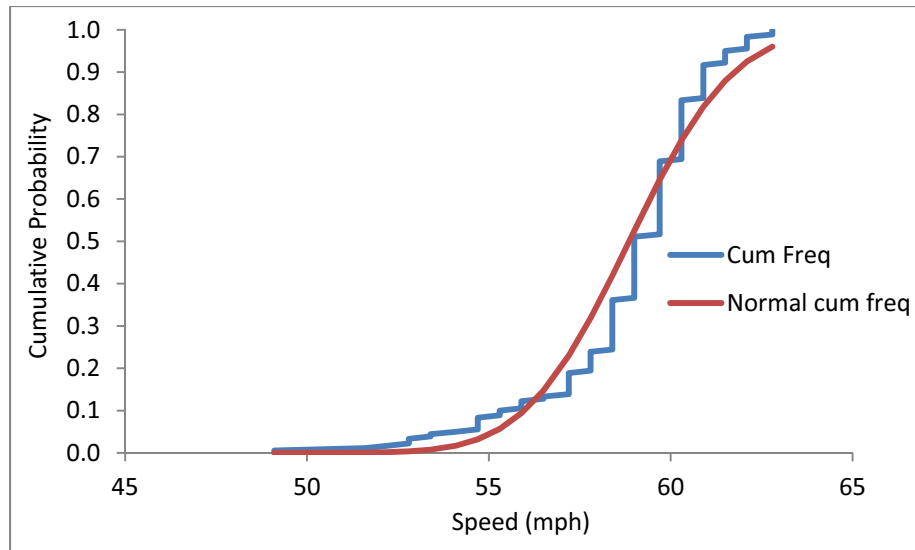


**Figure 8 Histogram of average speeds on a major arterial street segment**

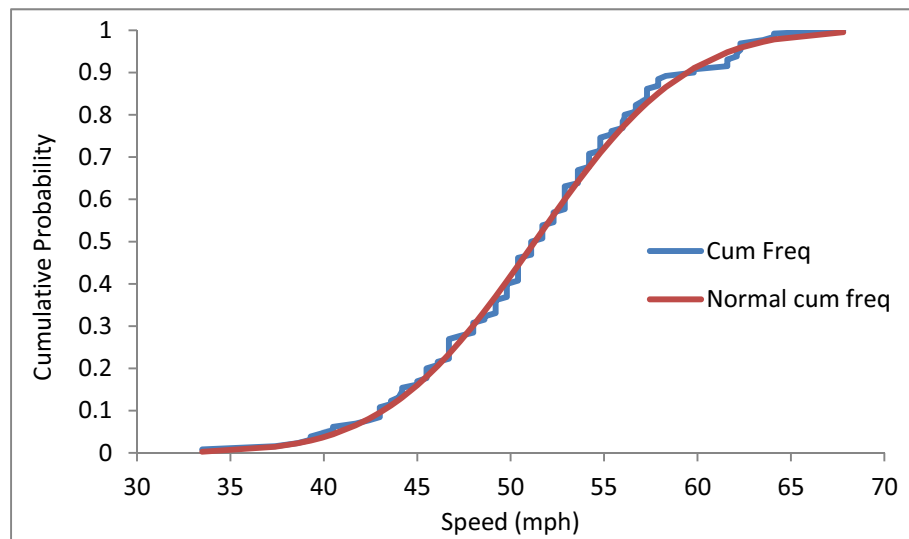


**Figure 9 Histogram of average speeds on a minor arterial street segment**

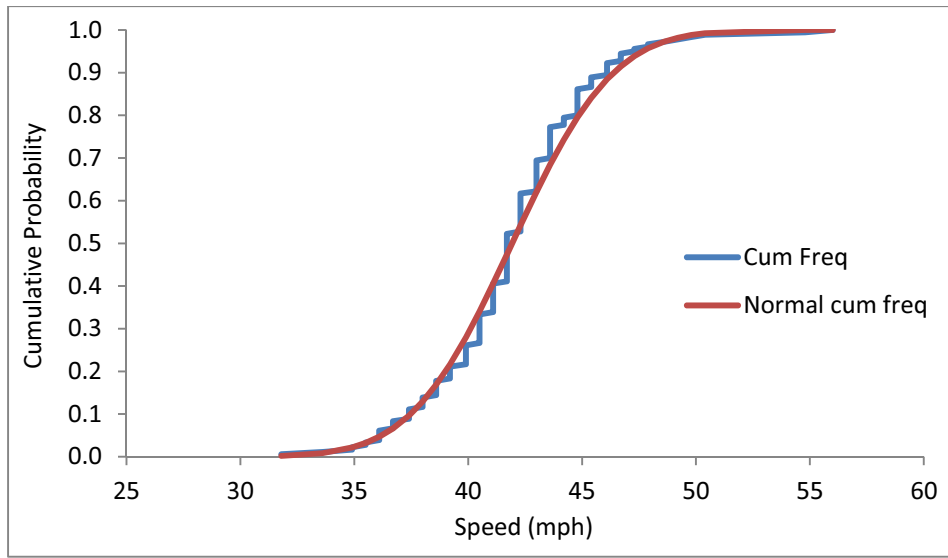
The corresponding cumulative distribution function plots are shown in Figure 10 through Figure 13. In these figures, the quantiles obtained from the INRIX speed data have been plotted along with the standard normal distribution quantiles, thus providing a side-by-side comparison to check for normality of data. The red line signifies normal distribution quantiles and the blue line represents quantiles for the INRIX speed data.



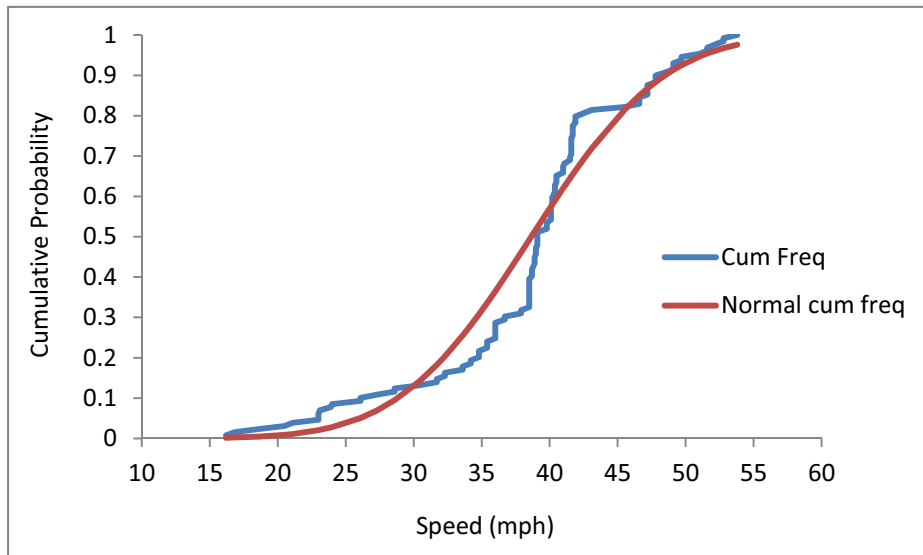
**Figure 10 CDF plot of average speeds on an Interstate segment (9PM-6AM, Mon-Fri)**



**Figure 11 CDF plot of average speeds on a freeway segment (9PM-6AM, Mon-Fri)**



**Figure 12 CDF plot of average speeds on a major arterial street segment**



**Figure 13 CDF plot of average speeds on a minor arterial street segment**



The histograms and the cumulative distribution function plots shown above suggest that travel speed data on most facility types follow normal distribution during unconstrained travel condition windows. The data for minor arterials show slight left skew which indicates that there is a relatively higher proportion of slower speeds on minor arterials compared to other facility types which follow normal distribution. One of the reasons for this observation can be that the reference time window for minor arterials is a daytime window, and therefore can witness some slower speeds relative to the traditional nighttime hours for the other two facility types.

The literature (21,23) suggests that the reasons for choosing the 85<sup>th</sup> percentile for defining reference speed on transportation facilities include:

- i. The gradient (slope) of the cumulative distribution curve changes at this percentile value. The gradient at or below this point is relatively sharp, while the slope becomes more gentle after it exceeds this point.
- ii. 15 percent of travelers are considered to be a fair number traveling in a more favorable/uncongested condition.
- iii. The 85<sup>th</sup> percentile value approximates mean speed plus one standard deviation of speeds if they are normally distributed, and thus includes 68% of the total data.

Another important rationale behind adopting the 85<sup>th</sup> percentile for defining reference speed in this study is that the data used is 15-minute average aggregated data. This aggregation process removes most of the driver-to-driver variation and the effects of very high individual speeds are minimized as a consequence. The distribution of 15-

minute average speeds indicate that groups of drivers (platoons of vehicles) are making different decisions in actuation and priority treatment scenarios as discussed in earlier sections in this chapter. Because we are looking for speeds that represent unconstrained conditions, and it is difficult to know from aggregated speeds why drivers are making different driving decisions, a higher percentile is a better reflection of “actual unconstrained” conditions.

As seen in the histogram and CDF plots in Figures 6 through 13, our speed data from INRIX during the chosen reference time windows (9PM-6AM for freeways and major arterials; 11AM-4PM for minor arterials) appear to follow normal distribution closely for both freeways and arterials. This is even more so because the maximum value of coefficient of variation within the chosen time windows was limited to 10 percent, thus limiting the variability. Chi-square test was performed to check for goodness of fit to normal distribution. Major arterial streets showed the highest conformity to normal distribution (10161 of 10927 segments [93%]) followed by uninterrupted flow facilities (91%) while approximately 68% of minor arterial segments (4167 of 6130) were found to follow the normal distribution.

The point of inflection, as pointed in the above reasons, seems to lie close to the 85<sup>th</sup> percentile for the INRIX travel speed database as well. Basing the percentile choice on the phenomenon of gradient change at that specific percentile seems rational. It suggests that the rate at which more people traveling at increasing speeds are being added to the sample remains constant until this percentile value, after which that rate drops, meaning these faster traveling people are getting added at a slower rate. Because

this study uses 15-minute aggregated speeds and not individual vehicle speeds, a lot of abnormally fast or slow driving population is already averaged out in the data. A few minor arterials show a slight negative skew, as seen in the histogram and CDF plots (Figure 9 and Figure 13), but for these too, the 85<sup>th</sup> percentile seems right about that point where the gradient change occurs.

Moreover, the 85<sup>th</sup> percentile is able to capture data within one standard deviation of the mean, and working with 15-minute averages, this results in being able to capture bulk of the speed distribution. Considering these, the 85<sup>th</sup> percentile average speed obtained from the identified travel windows gives a good representation of how the reference speed has been defined under this study. This observation remains applicable to all facilities included within this analysis. The time windows and magnitudes of reference speeds change with facility types, but the percentile seems to apply well to all cases.

The choice between average (mean) speed and the 85<sup>th</sup> percentile speed for defining the reference speed is debatable because both of these metrics have respective rationale for use as benchmark. This choice depends on a few factors including the objective behind the performance measurement exercise (which aspect(s) of system performance the agency/state is trying to capture), and also the robustness, level of aggregation and detail of data. However, this is one among the several aspects studied in this research. The focus of this research is also on determining which temporal windows are suitable for use in defining reference speed for different facility types. The answers

to these investigations can have broader implications on and bring incremental improvements to the area of transportation system performance measurement.

To summarize, the unconstrained travel window of 9 PM-6 AM on weekdays satisfies the criteria for high and consistent speeds for Interstate, Freeway and major arterial facilities. For minor arterial streets, a combination of low data availability within the 9 PM-6 AM time window and a visibly different travel pattern compared to the uninterrupted flow and major arterial facilities is observed. In order to satisfy the criteria set for unconstrained travel which allows high and consistent speeds over an appreciable period of time, a mid-day time window of 11 AM-4 PM on weekdays is recommended for minor arterial facilities. During these identified unconstrained travel windows, the 85<sup>th</sup> percentile of 15-minute aggregated speeds is recommended as the reference travel time.

## **CHAPTER V**

### **SUMMARY AND RECOMMENDATIONS**

Reference speed represents unconstrained travel conditions on transportation facilities and can be measured during daily temporal windows when the driver has a choice of travel speed unimpeded by other travelers. The purpose of this research study is to provide basis for benchmarking reference speed on transportation facilities with respect to which mobility and reliability performances of these facilities are measured. This has been done for two kinds of transportation facilities – uninterrupted flow facilities and interrupted flow facilities. Uninterrupted flow facilities are further sub-classified into interstates and freeways, and interrupted flow facilities into major arterial and minor arterial streets.

Review of available literature reveals that the state-of-practice varies among states and agencies in the United States as a few different metrics are used as reference speed for performance measurement. Some of these agencies define their reference speed as the Posted Speed Limit (PSL) or a variation based on the PSL. While this approach may work in certain situations, usually it lacks the adaptability to reflect operational conditions on roadways and actual traveler experience. It also requires a good PSL dataset. Using travel time data for all parts of the analysis is more consistent. Therefore, it is recommended that if sufficient travel data are available, reference speeds should be derived from a dataset of recorded actual travel times. Reference speed

obtained in such a manner is adaptive to changes in roadway operational conditions and can be updated periodically if needed.

Even among agencies which use reference speeds based on actual travel data, there is lack of consensus on the percentile value used to define reference speed. While some agencies use the mean travel speed within unconstrained travel window to define reference speed, a few others use the 67<sup>th</sup> percentile and several others adopt the 85<sup>th</sup> percentile as standard practice.

This study derives reference speed from travel speed data available from INRIX<sup>®</sup> by examining different candidate time windows throughout the day. The available database provides 15-minute aggregated speeds for rural and urban road segments on interrupted and uninterrupted flow facilities. For this study, the 85<sup>th</sup> percentile speed within the chosen unconstrained travel windows was defined as the reference speed. A rationale behind adopting the 85<sup>th</sup> percentile instead of other percentile values for defining reference speed in this study is that the 15-minute data aggregation process removes most of the driver-to-driver variation. Because of this reduction in variability in individual driver behavior, the 85<sup>th</sup> percentile in this case better approximates reference speed than in the case where individual driver speeds are used without aggregation and the 85<sup>th</sup> percentile may likely overestimate reference speeds.

The distribution of 15-minute average speeds indicate that groups of drivers (platoons of vehicles) are making different decisions because of signal-timing related phenomena such as actuation and priority treatment where a much higher proportion of signal cycle length is allocated to the major street, thereby reducing the green time on

minor street. Because we are looking for speeds that represent unconstrained conditions, and it is difficult to know from aggregated speeds why drivers are making different driving decisions, a higher percentile is a better reflection of “actual unconstrained” conditions.

Based on review of available literature on the subject, the 85<sup>th</sup> percentile value provides a reasonable threshold for defining a reference value such as one under the scope of this study. This is primarily because of three reasons:

- i. The gradient (slope) of the cumulative distribution curve changes at this percentile value. The gradient at or below this point is relatively sharp, while the slope becomes more gentle after it exceeds this point. In this study’s context, it means that the rate at which more people traveling at increasing speeds are being added to the sample remains constant up to this percentile level, after which the rate drops, meaning the faster traveling samples are getting added to the population at a slower rate.
- ii. 15 percent of travelers are considered to be a fair number traveling in a more favorable/uncongested condition than the reference conditions.
- iii. The 85<sup>th</sup> percentile value approximates mean speed plus one standard deviation of speeds if they are normally distributed, and thus includes 68 percent of the total data. Working with 15-minute average values as in this study, it results in being able to capture bulk of the speed distribution.

The occurrence of change in gradient to define the threshold value is observed with the speed data in this study as well. This observation is in line with previous studies and the

value of threshold lies very close to the 85<sup>th</sup> percentile value as seen in the normal quantile (CDF) plots discussed in Chapter 4.

Based on time windows which satisfied defined criteria for data adequacy and variability, it was observed that the most preferred time intervals for uninterrupted and interrupted facilities are 11 PM-5 AM and 9 PM-6 AM respectively. The use of a common time window for both interrupted as well as uninterrupted facilities was also examined. It was found that using the interrupted flow time window (9 PM-6 AM) for uninterrupted flow facilities did not have a statistically significant impact on reference speeds for approximately 90 percent (9,529 of 10,584) of all uninterrupted flow facilities.

An interesting observation relates to occurrences of lower travel speeds during traditional nighttime hours for minor arterial streets compared to mid-day travel speeds. On average, the 85<sup>th</sup> percentile speed value reflected slightly higher speed (5.7 percent) during the midday unconstrained travel period compared to nighttime unconstrained travel period for all minor arterial streets. The possible reasons for this observation include use of actuated signal control for minor arterials or pre-timed control which prioritizes major street traffic. This causes the minor street traffic to experience moderate to high travel times even when the traffic is very light during overnight hours compared to similar traffic levels during mid-day periods. During nighttime free-flow conditions, vehicles which are able to get uninterrupted service at minor street intersections are able to register lower travel times (higher average speeds), while those which need to wait for the green indication because of actuation or priority treatment experience a higher travel



time. This gives rise to an overall higher fluctuation in travel time. The coefficient of variation decreased from 16.4 percent during traditional unconstrained travel period (9 PM-6 AM) to 7.2 percent during mid-day period (11AM-4 PM). Based on these travel pattern observations, a different time window (11 AM-4 PM) was found to be more appropriate while fulfilling the criteria for identifying reference speed on minor arterial streets.

It was found that including weekend data in the analysis did not have a statistically significant impact on the value of reference speed for 89.9 percent of all facilities. Although a small proportion of these facilities experienced an increase in values of reference speeds when weekend travel data (5 AM-9 AM) were included in the analysis, this change was found to be statistically insignificant. This seems to be intuitive because travel behavior for a driver familiar with the facility does not change significantly during typically low traffic periods and when traffic pressure does not have an effect on driving behavior.

Travel speed data for three classes of facilities – interstates, freeways and major arterial streets – were found to be normally distributed during the recommended unconstrained travel time windows based on the statistical tests conducted. Based on the Chi-square test for goodness of fit to normal distribution, major arterial segments showed the highest conformity to normal distribution (93%) followed by uninterrupted flow facilities (91%) and minor arterial segments (68%). The speed data for minor arterials show a slight negative skew. This may have been caused because of the fact that the minor arterials use a mid-day period for reference analysis and it is relatively more

likely for a small proportion of vehicles to witness slower speeds compared to the traditional nighttime hours for the other three facility types. The mean of speed distribution is prone to be affected by this small proportion of slower driving vehicles, however the reference speed is not affected as much because it is a higher percentile of the speed data distribution which is still determined by the portion of driver population traveling at higher than average speed.

This research suggests use of different time windows of unconstrained travel identified for different classes of transportation facilities. These windows are 9 PM- 6 AM on weekdays for interstates, freeways and major arterial streets, and 11 AM-4 PM on minor arterial streets. The 85<sup>th</sup> percentile value of aggregated travel speeds is a reasonable measure of reference speed which can be used for performance measurement activities. A snapshot of key recommendations is provided in Table 8.

**Table 8: Key Recommendations of the Study for Different Facility Types**

Facility Type	Time Window	Speed Percentile	Notes
Freeways and Interstates	9 PM – 6 AM weekdays (Mon-Fri)	85 <sup>th</sup> percentile of average speeds within chosen time window	Mostly adequate, consistent and normal data
Major arterial			Most normal data, moderate data adequacy
Minor arterial	11 AM – 4 PM weekdays (Mon-Fri)		Shows left skew in speed distribution, low data availability during nighttime period

Use of reference speed based on actual travel time (speed) data instead of fixed reference based on posted speed limit value has advantages of being adaptive, updateable on a periodic basis and a closer representative of prevailing operational conditions and driver experience. This also does away with the requirement of inventory data (for posted speed limits) in addition to speed database. The balance between adequacy of data and its variability within identified time windows should be considered while performing performance measurement analyses.

The outputs of this research can have wide applications in the area of transportation system performance measurement, particularly in mobility and reliability measurement applications. It can eventually better inform decision-making by public and private agencies, and improve transportation funding activities through proper appropriation of funds based on agency's objectives, need and current performance of their transportation systems.

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